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Chinese Journal of Aeronauticsjournal homepage: www.elsevier.com/locate/cja

A User Differential Range Error Calculating Algorithm Based on Analytic Method

SHAO Bo, LIU Jiansheng, ZHAO Ruibin, HUANG Zhigang, LI Rui*

School of Electronics and Information Engineering, Beihang University, Beijing 100191, China

Received 22 November 2010; revised 27 May 2011; accepted 28 June 2011

Abstract

To enhance the integrity, an analytic method (AM) which has less execution time is proposed to calculate the user differential range error (UDRE) used by the user to detect the potential risk. An ephemeris and clock correction calculation method is introduced first. It shows that the most important thing of computing UDRE is to find the worst user location (WUL) in the service volume. Then, a UDRE algorithm using AM is described to solve this problem. By using the covariance matrix of the error vector, the searching of WUL is converted to an analytic geometry problem. The location of WUL can be obtained directly by mathematical derivation. Experiments are conducted to compare the performance between the proposed AM algorithm and the exhaustive grid search (EGS) method used in the master station. The results show that the correctness of the AM algorithm can be proved by the EGS method and the AM algorithm can reduce the calculation time by more than 90%. The computational complexity of this proposed algorithm is better than that of EGS. Thereby this algorithm is more suitable for computing UDRE at the master station.

Keywords: satellite navigation; user differential range error; integrity; analytic method; worst user location

1. Introduction

With the development of the satellite based augmentation system (SBAS), the integrity becomes increasingly more important in the global navigation satellite system (GNSS) application domain such as safety of life^[1–4]. The International Civil Aviation Organization (ICAO) defines integrity as “a measure of the trust that is placed in the correctness of the information supplied by the total system”. Integrity includes the ability of a system to provide timely and valid warnings to the user (alerts)^[5]. In order to ensure the safety of users, one of the most important guideline is that the SBAS should send the satellite integrity messages and

correction data to SBAS users within a time-to-alert (TTA) limit^[6].

Integrity data, such as user differential range error (UDRE), are used to calculate horizontal protection level (HPL) or/and vertical protection level (VPL) which are the reflection of the horizontal protection error (HPE) and vertical protection error (VPE)^[7–9]. The user receiver compares the protection levels with the alert limit. If any of the protection levels exceeds the corresponding alert limit, the receiver ought to provide an annunciation to the pilot^[10].

The UDRE has been researched by many scholars^[11–16]. Typically, an exhaustive grid search (EGS) method through a $1^\circ \times 1^\circ$ grid point searching is proposed by Blomenhofer, et al.^[14]. In Ref. [13], Chen provided a UDRE verification algorithm which was used to verify the correctness of UDRE but it could not calculate UDRE in real time. As shown in Ref. [15], Ma calculated the projection of residual error on several reference points in the service volume and chose the maximal as the UDRE. The UDRE calculated by this

*Corresponding author. Tel.: +86-10-82339223.

E-mail address: lee_ruin@263.net

Foundation item: National Basic Research Program of China (2010CB731805)

method cannot envelope the maximum residual error caused by the ephemeris and clock corrections in the service volume.

To envelope the projection of residual error at any place in the satellite coverage, the UDRE calculation needs to be based on the worst user location (WUL) that has the maximum residual error^[17-18]. Then, the UDRE must be sent to the users within TTA. Otherwise, the user may not calculate the HPL/VPL in time and, thus, encounter an integrity risk. In this situation, the receiver will not alert the user that a risk is happening. According to Ref. [19], TTA is influenced by several factors, such as the processing ability of the master station and the delay of the communication network. Therefore, improving the UDRE computing algorithm of the master station is one of the effective approaches to enhance the integrity ability of SBAS.

In this paper, an ephemeris and clock correction calculation method is introduced in brief. Based on this method, an analytic method (AM) for the computation of WUL is proposed. The finding of the WUL is changed to an analytic geometry problem by using the covariance matrix of the error vector. Then, the location of WUL can be obtained by derivation. Experiments are performed to compare the performance between the proposed AM algorithm and the EGS method. The results indicate that the computational complexity of the proposed method is lower. It means that this method is quite suitable for computing the UDRE in the master station of SBAS.

2. UDRE Algorithm

SBAS is a combination of ground-based and space-based equipment to augment the global positioning system (GPS). A network of ground reference stations with precisely surveyed GPS antennas is strategically positioned to collect GPS satellite data across the service volume^[10]. At each reference station, the code and carrier phase measurements are obtained by the dual frequency (cross-correlating) receivers and the pseudorange residual error is calculated using these measurements. Then, the residual error of every reference station is sent to the master station where the ephemeris correction, clock correction and UDRE are generated.

2.1. Ephemeris and clock corrections

The pseudorange residual error is computed by removing geometric range, satellite clock bias, ionospheric delay and tropospheric delay from the carrier smoothed pseudorange^[6]. At this point, the pseudorange residual error only includes the ephemeris error, the satellite clock error and measurement noise as

$$\Delta\rho_{0,c} = H_0\Delta R^j - H_c\Delta B^j + V \quad (1)$$

where $\Delta\rho_{0,c} = [\Delta\rho_1^j \ \Delta\rho_2^j \ \cdots \ \Delta\rho_M^j]^T$, $\Delta\rho_i^j$ is the

pseudorange residual error for the j th satellite at the i th reference station, M the number of reference stations that can observe the j th satellite; ΔR^j and ΔB^j are the ephemeris error vector and the clock error of the j th satellite respectively; $H_0 = [I_1^j \ I_2^j \ \cdots \ I_M^j]_{M \times 3}$, I_i^j is the unit direction vector from the reference station to the satellite; $H_c = [1 \ 1 \ \cdots \ 1]_{M \times 1}^T$; $V = [v_1^j \ v_2^j \ \cdots \ v_M^j]^T$, v_i^j is the measurement noise which accounts for the error in carrier smoothing, ionospheric delay estimation and tropospheric delay estimation. The standard deviation of v_i^j is σ and the covariance matrix of V is $A_V = \sigma^2 I_{M \times M}$.

To separate the satellite clock error from the ephemeris error, single differencing is required^[11], which will make the ephemeris error and clock error independent from each other and benefit the calculation of the UDRE by using the analytic method. This will be explained later.

After single differencing, the satellite clock error is removed from the pseudorange residual error.

$$\Delta\rho_{os} = H_{os}\Delta R^j + V_{os} \quad (2)$$

where $\Delta\rho_{os} = [\Delta\rho_1^j - \Delta\rho_k^j \ \Delta\rho_2^j - \Delta\rho_k^j \ \cdots \ \Delta\rho_M^j - \Delta\rho_k^j]_{(M-1) \times 1}^T$, $H_{os} = [I_1^j - I_k^j \ I_2^j - I_k^j \ \cdots \ I_M^j - I_k^j]_{(M-1) \times 3}$, V_{os} is the noise vector with a covariance matrix A_{os} .

Then, a weighted least square (WLS) estimator is used to estimate ephemeris error ΔR^j from Eq. (2). The satellite ephemeris correction and its accuracy can be written as

$$\Delta\hat{R}^j = (H_{os}^T A_{os}^{-1} H_{os})^{-1} H_{os}^T A_{os}^{-1} \Delta\rho_{os} \quad (3)$$

$$P_o = (H_{os}^T A_{os}^{-1} H_{os})^{-1} \quad (4)$$

Removing the ephemeris error from Eq. (1), the expression used to compute satellite clock correction is expressed as follows:

$$\Delta\rho_c = H_c\Delta B^j + V_o \quad (5)$$

where the covariance matrix of V_o is A_o .

Just like the calculation of the satellite ephemeris correction, the clock correction is computed by a WLS estimator as well. The expressions of clock correction and its accuracy are

$$\Delta\hat{B}^j = (H_c^T A_o^{-1} H_c)^{-1} H_c^T A_o^{-1} \Delta\rho_c \quad (6)$$

$$P_c = (H_c^T A_o^{-1} H_c)^{-1} \quad (7)$$

2.2. Calculation of WUL using analytic method

Removing ephemeris and clock corrections from the true values, the error vector can be written as

$$\varepsilon^j = [(\Delta R^j)^T \ \Delta B^j]^T - [(\Delta\hat{R}^j)^T \ \Delta\hat{B}^j]^T \quad (8)$$

Because the calculation of the satellite ephemeris

and clock corrections are separate, $\Delta\hat{\mathbf{R}}^j$ and $\Delta\hat{\mathbf{B}}^j$ are independent from each other. In other words, the correlation coefficient between $(\Delta\mathbf{R}^j - \Delta\hat{\mathbf{R}}^j)$ and $(\Delta\mathbf{B}^j - \Delta\hat{\mathbf{B}}^j)$ is zero. Thus, the covariance matrix of $\boldsymbol{\varepsilon}^j$ is expressed as

$$\mathbf{P}_{\text{UDRE}} = \begin{bmatrix} \mathbf{P}_0 & 0 \\ 0 & P_c \end{bmatrix} \quad (9)$$

The variance of the projection of $\boldsymbol{\varepsilon}^j$ onto a user can be written as

$$(\boldsymbol{\sigma}_{\text{user}}^j)^2 = (\mathbf{u}_{\text{user}}^j)^T \mathbf{P}_{\text{UDRE}} \mathbf{u}_{\text{user}}^j \quad (10)$$

where $\mathbf{u}_{\text{user}}^j = [(\mathbf{l}_{\text{user}}^j)^T \ 1]^T$, and $\mathbf{l}_{\text{user}}^j$ is the unit direction vector from the user to the j th satellite.

The UDRE broadcasted in wide area augmentation system (WAAS) message type 6 is a scalar, but it must bound the maximum residual error (due to imprecise ephemeris and clock corrections) in the satellite coverage with the probability of 99.9%. Otherwise an integrity alert should be raised. Therefore, the UDRE is computed for the so-called WUL where the residual error becomes maximal. The requirement of WUL can be written as

$$(\mathbf{u}_{\text{WUL}}^j)^T \mathbf{P}_{\text{UDRE}} \mathbf{u}_{\text{WUL}}^j = \max_{\text{userservice_volume}} ((\mathbf{u}_{\text{user}}^j)^T \mathbf{P}_{\text{UDRE}} \mathbf{u}_{\text{user}}^j) \quad (11)$$

where $\mathbf{u}_{\text{WUL}}^j = [(\mathbf{l}_{\text{WUL}}^j)^T \ 1]^T$, and $\mathbf{l}_{\text{WUL}}^j$ is the unit direction vector from the WUL to the j th satellite.

It is possible to compute both $\Delta\mathbf{R}^j$ and $\Delta\mathbf{B}^j$ simultaneously in a WLS estimator and the corrections can provide adequate integrity and availability for the users. But this strategy will make ephemeris and clock error influence each other and the finding of WUL should then be carried out in a four-dimensional space (three represent position and one represents time), which is not an easy task. By using single differencing, $\Delta\hat{\mathbf{R}}^j$ and $\Delta\hat{\mathbf{B}}^j$ are independent from each other. Since $\Delta\hat{\mathbf{B}}^j$ is the same as all the users in the j th satellite coverage, WUL is only influenced by $\Delta\hat{\mathbf{R}}^j$. Eq. (11) can be simplified to

$$(\mathbf{l}_{\text{WUL}}^j)^T \mathbf{P}_0 \mathbf{l}_{\text{WUL}}^j = \max_{\text{userservice_volume}} ((\mathbf{l}_{\text{user}}^j)^T \mathbf{P}_0 \mathbf{l}_{\text{user}}^j) \quad (12)$$

Due to \mathbf{P}_0 which is a real symmetric matrix, there exists a unit orthogonal transformation matrix, \mathbf{C} , which satisfies

$$\mathbf{C}^T \mathbf{P}_0 \mathbf{C} = \mathbf{P}_Y = \text{diag}(\lambda_1, \lambda_2, \lambda_3) \quad (13)$$

where $\lambda_1 \geq \lambda_2 \geq \lambda_3 > 0$ is the eigenvalue of \mathbf{P}_0 ; the column vector of \mathbf{C} is the eigenvector of \mathbf{P}_0 about λ_i ($i=1, 2, 3$).

Using \mathbf{C} , the Earth-centered Earth-fixed (ECEF) coordinate system can be transformed to a new coordinate system whose origin is the position of the satellite (see Fig. 1). In Fig. 1, r_e is the radius of the Earth, ε the mask angle of the user, δ the geocentric angle, α the zenith angle, β the acute angle between x axis and vector $\overrightarrow{OO'}$.

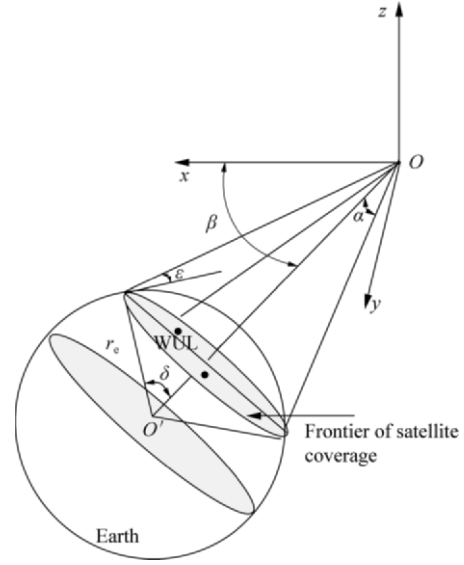


Fig. 1 New coordinate system and location of WUL when $\beta > \alpha$.

In the World Geodetic System 1984 (WGS 84), the flat rate of the Earth is 0.003 35 which is quite small. Therefore the Earth is treated as a sphere here. The coordinates of a user on the Earth need to satisfy

$$|\mathbf{X}_u - \mathbf{X}_0| = r_e \quad (14)$$

where $\mathbf{X}_u = [x_u \ y_u \ z_u]^T$ is the user position and its unit direction vector to the satellite is $\mathbf{X}_u/|\mathbf{X}_u|$, $\mathbf{X}_0 = [x_0 \ y_0 \ z_0]^T = -\mathbf{C}^T \mathbf{X}_s$ the position of the origin (at the center of the Earth) of ECEF in the new coordinate system.

According to Eqs. (12)-(13), WUL is the \mathbf{X}_u which makes $f(\mathbf{X}_u) = \frac{\mathbf{X}_u^T}{|\mathbf{X}_u|} \mathbf{P}_Y \frac{\mathbf{X}_u}{|\mathbf{X}_u|}$ reach the maximum in the satellite coverage. $\mathbf{X}_u/|\mathbf{X}_u|$ can be written as $[\cos\theta \ \sin\theta\cos\varphi \ \sin\theta\sin\varphi]^T$ where θ is the angle between vector $\mathbf{X}_u/|\mathbf{X}_u|$ and the x axis, while φ is the angle between the projection of $\mathbf{X}_u/|\mathbf{X}_u|$ on the plane yOz and the y axis.

Then, $f(\mathbf{X}_u)$ can be rewritten as

$$f(\mathbf{X}_u) = f(\theta, \varphi) = \lambda_1 \cos^2 \theta + \lambda_2 \sin^2 \theta \cos^2 \varphi + \lambda_3 \sin^2 \theta \sin^2 \varphi \quad (15)$$

The distance from a point $(\sqrt{\lambda_1} \cos \theta, \sqrt{\lambda_2} \sin \theta \cos \varphi, \sqrt{\lambda_3} \sin \theta \sin \varphi)$ on the ellipsoid $\frac{x^2}{\lambda_1} + \frac{y^2}{\lambda_2} + \frac{z^2}{\lambda_3} = 1$ to the origin is

$$d = \sqrt{\lambda_1 \cos^2 \theta + \lambda_2 \sin^2 \theta \cos^2 \varphi + \lambda_3 \sin^2 \theta \sin^2 \varphi} \quad (16)$$

From Eqs. (15)-(16), it can be deduced that

$$f(\mathbf{X}_u) = d^2 \quad (17)$$

Since $\lambda_1 \geq \lambda_2 \geq \lambda_3$, the maximum distance from the point on the ellipsoid to the origin is $\sqrt{\lambda_1}$. Thereby the maximum value of Eq. (15) is $f(0,0) = \lambda_1$. In this case,

$\mathbf{X}_u/|\mathbf{X}_u|=[1 \ 0 \ 0]^T$. Because WUL must be in the satellite coverage, the acute angle between vector $\mathbf{X}_u/|\mathbf{X}_u|$ and vector $\overrightarrow{OO'}$ must be no bigger than α . α is determined by the law of sine:

$$\sin \alpha = (r_e \cos \varepsilon) / r_s \quad (18)$$

where $r_s = \sqrt{x_0^2 + y_0^2 + z_0^2}$.

There are two cases about the relationship between α and β . One is $\beta \leq \alpha$ while the other is $\beta > \alpha$.

When $\beta \leq \alpha$, \mathbf{X}_u that makes $f(\mathbf{X}_u)$ maximal must also satisfy $\mathbf{X}_u/|\mathbf{X}_u|=[1 \ 0 \ 0]^T$. Therefore WUL is the intersection point between x axis and the Earth surface as shown in Fig. 2, and the coordinates of WUL are

$$\mathbf{X}_u = [x_0 \pm \sqrt{r_e^2 - y_0^2 - z_0^2} \ 0 \ 0]^T \quad (19)$$

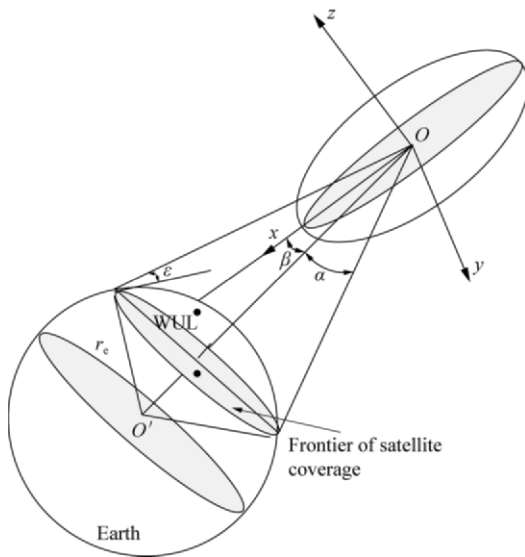


Fig. 2 Location of WUL when $\beta \leq \alpha$.

There are two points in Eq. (19). One is on the back side of the Earth and cannot receive the signal from the satellite (the elevation angle of this point is minus). The other one is the WUL coordinate.

When $\beta > \alpha$, according to the experimental result which will be shown later, λ_1 , λ_2 and λ_3 meet $\lambda_1 \gg \lambda_2$ and $\lambda_1 \gg \lambda_3$. Thus, Eq. (15) can be changed to

$$f(\theta, \varphi) \approx \lambda_1 \cos^2 \theta + \lambda_2 \quad (20)$$

From Eq. (20), it can be concluded that a smaller θ will yield a bigger $f(\theta, \varphi)$. Therefore, \mathbf{X}_u that makes $f(\mathbf{X}_u)$ maximal is the intersection point between the plane made up by x axis, vector $\overrightarrow{OO'}$ and the frontier of the satellite coverage as shown in Fig. 1, and the expressions are

$$\begin{cases} x_u^2 + y_u^2 + z_u^2 = \left(\frac{r_s - r_e \cos \delta}{\cos \alpha} \right)^2 \\ x_1 x_u + y_1 y_u + z_1 z_u = r_s - r_e \cos \delta \\ z_1 y_u - y_1 z_u = 0 \end{cases} \quad (21)$$

where $\delta = 90^\circ - \alpha - \varepsilon$, $[x_1 \ y_1 \ z_1]^T = \mathbf{X}_0/|\mathbf{X}_0|$.

From Eq. (21), the coordinates of WUL are

$$\begin{cases} x_u = \frac{(r_s - r_e \cos \delta) y_1 - (1 - x_1^2) y_u}{x_1 y_1} \\ y_u = (r_s - r_e \cos \delta) y_1 \pm a_0 \\ z_u = \frac{z_1}{y_1} y_u \end{cases} \quad (22)$$

where $a_0 = (r_s - r_e \cos \delta) |y_1| \sqrt{\frac{x_1^2 - \cos^2 \alpha}{(1 - x_1^2) \cos^2 \alpha} + 1}$.

There are two points in Eq. (22) and only the one which makes $f(\mathbf{X}_u)$ bigger than the other one is the satisfied point.

The UDRE of the satellite coverage is

$$V_{\text{UDRE}} = 3.29 \sqrt{\mathbf{g}_{\text{WUL}}^T \begin{bmatrix} \mathbf{P}_Y & 0 \\ 0 & P_c \end{bmatrix} \mathbf{g}_{\text{WUL}}} \quad (23)$$

where $\mathbf{g}_{\text{WUL}} = [\mathbf{X}_{\text{WUL}}^T / |\mathbf{X}_{\text{WUL}}| \ 1]^T$ and \mathbf{X}_{WUL} are obtained from Eq. (19) or Eq. (22).

3. Simulation Results

Experiments are made to compare the performance of the AM algorithm and EGS stepped by $1^\circ \times 1^\circ$ by using MATLAB. The hardware of the computer used in the experiments is Intel Pentium Dual CPU 2.00 GHz and memory bank 2.00 GB. Two satellites are chosen randomly for the experiments according to the two situations described in the AM algorithm. The satellite coordinate at some epoch in ECEF and the relative parameters (such as the eigenvalues of \mathbf{P}_0) are shown in Table 1. From Table 1, it is obvious that $\lambda_1 \gg \lambda_2$ and $\lambda_1 \gg \lambda_3$ when $\beta > \alpha$.

Table 1 Satellite coordinate and relative parameters

Parameter	Satellite 1	Satellite 2
x coordinate/m	11 432 916.501 2	-14 087 109.663 5
y coordinate/m	19 802 392.258 8	-8 196 660.574 6
z coordinate/m	15 986 311.225 2	20 971 449.562 5
$\alpha/^\circ$	12.757 1	13.412 4
$\beta/^\circ$	8.544 8	13.533 6
λ_1/m^2	0.981 2	0.561 6
λ_2/m^2	$0.141 7 \times 10^{-2}$	$0.218 5 \times 10^{-4}$
λ_3/m^2	$0.517 2 \times 10^{-3}$	$0.117 0 \times 10^{-3}$
P_c/m^2	0.337 9	0.338 7

WUL and UDRE of the AM algorithm and EGS method are shown in Table 2. From this table, the WUL found by AM is more accurate. This is because the AM algorithm directly derives the WUL by using analytic geometry method, while the EGS depends on the way of the grid divided and cannot scout the entire solution space exhaustively. In this simulation, the WULs obtained by the two methods are very similar

which results in the fact that there is no significant difference between the unite vectors (from the WULs to the satellite), and thus the UDREs are the same. This demonstrates the correctness of the AM algorithm to some extent.

Table 2 Performance of AM against EGS

Satellite	Method	Longitude/(°)	Latitude/(°)	UDRE/m
Satellite 1	AM	99.098 2	34.198 2	3.778 6
	EGS	99	34	3.778 6
Satellite 2	AM	115.165 9	40.854 9	3.121 7
	EGS	115	41	3.121 7

The TTA limit for the Category I Approach (CAT I) is 6 s^[9]. The TTA budget for the master station integrity data processing is 1 s^[19]. To enhance the integrity ability of SBAS, one strategy is to save the UDRE computing time at master station.

Computational complexity, here, is chosen as the index to compare the performance between the AM algorithm and EGS method. The computational complexity of an algorithm quantifies the amount of time taken by the algorithm to run as a function of the size of the input to the problem. It is estimated by counting the number of mathematical operations performed by the algorithm (it usually takes a fixed amount of time to perform a mathematic operation) and is commonly expressed as “ O ”. For example, if the time required by an algorithm is at most $32n+10$, the computational complexity of this algorithm is $O(n)$, where n is the

number of the candidate user grids in the satellite coverage.

The computational complexity of the AM algorithm and EGS method is detailed in Table 3. The number of mathematical operations of EGS is $101+78n$. The number of the valid statements is $210+31n$. Thus, the time complexity of the EGS is $O(n)$ which is in a linear order. It can be deduced that the execution time of EGS is influenced not only by the hardware of the computer but also by the quantity of n . The bigger n becomes, the longer time will be spent. In these experiments, the execution time of EGS for the two satellites is 2.815 8 s and 3.484 5 s respectively.

On the other hand, the numbers of mathematical operations of AM algorithm for the two satellites are 546 and 635. The numbers of valid statements of AM are 219 and 235. These are quite small compared to EGS. Neither the number of mathematical operations nor the number of valid statements is influenced by n . Consequently, the time complexity of the AM is $O(1)$, which is constant order and is better than that of EGS. The execution time of AM for the two satellites is 0.026 74 s and 0.027 01 s, respectively, which only depend on the hardware of the computer. For the AM algorithm which does not need to calculate every candidate location in the satellite coverage, more than 90% of execution time is reduced. Therefore the AM algorithm seems to be a better choice to calculate UDRE at the master station to enhance the integrity.

Table 3 Computational complexity of different methods

Satellite	Method	Time complexity	n	Mathematical operation	Valid statement	Execution time/s
Satellite 1	AM	$O(1)$	—	546	219	0.026 74
	EGS	$O(n)$	21524	$101+78n$	$210+31n$	2.815 8
Satellite 2	AM	$O(1)$	—	635	235	0.027 01
	EGS	$O(n)$	23110	$101+78n$	$210+31n$	3.484 5

4. Conclusions

(1) An AM algorithm is proposed to improve the UDRE computational complexity in this work. In this method, the location of WUL is obtained by mathematical derivation.

(2) Experiments are made to compare the performance of the proposed AM algorithm with that of the EGS method. Through analyzing the results, the correctness of the AM algorithm is proved by the EGS method while the computational complexity of this proposed algorithm is better than that of original EGS method. The proposed AM algorithm can reduce the calculation time by more than 90%. Therefore this algorithm is an attractive choice to estimate UDRE at the master station.

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Biographies:

SHAO Bo Born in 1983, he received B.S. degree in electronic engineering from Zhengzhou University, Henan, China in 2005. Now he is in pursuit of Ph.D. degree in Beihang University, Beijing, China. He carries out research on integrity monitoring techniques of satellite based augmentation system.

E-mail: boris_shiu@yahoo.cn

LIU Jiansheng Born in 1965, he received Ph.D. degree in electronics from Ulster University, U.K. in 1998. Now he is a professor of School of Electronics and Information Engineering in Beihang University, China. His research interests include optical information system, optical fiber sensor and optical communication.

E-mail: jsliu@buaa.edu.cn

ZHAO Ruibin Born in 1975, he received B.S. and M.S. degrees in the Second Aeronautical Institute of the Air Force and Inner Mongolia University of Technology, in 1998 and 2007 respectively. Now he is a Ph.D. candidate in Beihang University, Beijing, China. He carries out research on global navigation satellite system.

E-mail: zhrbdove@foxmail.com

HUANG Zhigang Born in 1962, he received Ph.D. degree in electronics from Beihang University (BUAA), Beijing, China in 2004. Now he is a professor of School of Electronics and Information Engineering in BUAA. His research interests include integrity algorithms and related software for GBAS and SBAS.

E-mail: baahzg@163.com

LI Rui Born in 1975, he received Ph.D. degree in radio navigation from Beihang University (BUAA), Beijing, China in 2007. Now, he is a lecturer of School of Electronics and Information Engineering in BUAA. His main interests cover TIS, INS, GNSS and their integration application.

E-mail: lee_ruin@263.net